Wide Field Infrared Survey Telescope (WFIRST)

A Collection of One Page Science Programs

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http://wfirst.gsfc.nasa.gov/

Prepared by the WFIRST Science Definition Team (SDT) with contributions from SDT consultants and members of the broader astronomical community.

Hilke E. Schlichting (UCLA), hilke@ucla.edu

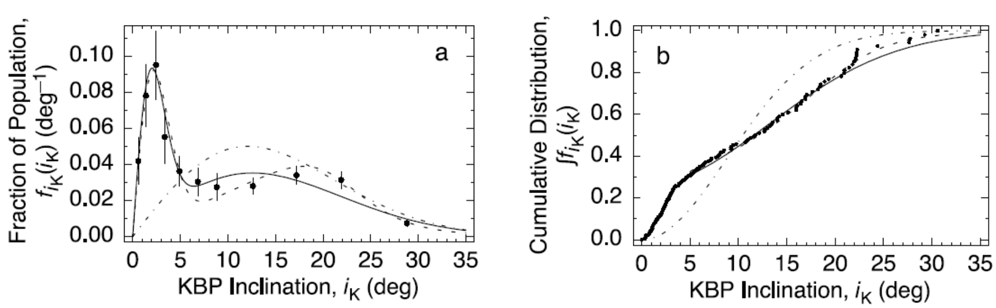
A Full Portrait of the Kuiper Belt, including Size Distributions, Colors and Binarity

Background

The Kuiper belt is a remnant of the primordial Solar system. It consists of a disk of icy bodies located at the outskirts of our planetary system, just beyond the orbit of Neptune, and is the likely source of short period comets. More than 1200 Kuiper Belt Objects (KBOs) have been detected since its discovery in 1992 (Jewitt & Luu 1993). In the Kuiper Belt, planet formation never reached completion and as a result it contains some of the least processed bodies in our Solar system. Its dynamical and physical properties illuminate the conditions during the early stages of planet formation and have already led to major advances in the understanding of the history of our planetary system. However, despite all these successes, many open questions remain: is the Kuiper Belt undergoing collisional evolution, grinding small KBOs to dust and therefore a true analogue to the dust producing debris disk around other stars? How did Neptune's outward migration proceed (Malhotra 1993, Tsiganis et al. 2005)? And what do the colors of KBOs imply about their formation and consequent evolution? Only a deep, uniform wide-field survey will be able to definitively answer these and other questions.

WFIRST

WFIRST will enable a uniform wide-field survey with unprecedented sensitivity of the Kuiper Belt. Since there are estimated to be more than 4 x 10^4 KBOs with diameters greater than 100km (R ~ 24), WFIRST will increase the current number of known KBOs by at least an order of magnitude. WFIRST has the potential to provide us with an almost complete census of KBOs with magnitudes of R< 25 (m_{F087} ~ 25.7). This will yield the best measurement of the KBO size distribution below the observed break at R ~ 24, which will provide important constraints on the material properties of KBOs and their collisional evolution. In addition, WFIRST will enable us to make, for the first time, detailed comparisons between the size distributions of KBOs in different dynamical classes, shedding light onto the origin of the break in the KBO size distribution and the planet formation process itself. Furthermore, WFIRST will provide a detailed census of the resonant population in the Kuiper Belt and should discover 100s – 1000s of binaries, which together provide important constraints on Neptune's migration history. Finally, it will provide a uniform survey of KBO colors over a wide range of sizes. Comparison between the colors of small KBOs whose sizes are below the break radius with that of larger KBOs will, for example, show if some of the color diversity in the Kuiper belt can be attributed to collisional resurfacing.



Caption: Unbiased inclination distribution of KBOs from Elliot et al. (2005).

Key Requirements

Coverage – Ideally ~14,000 deg^2 (+/- 20^o of the ecliptic), but ~7,000 deg^2 suffices to discover the majority of KBOs (assuming distribution of fainter (smaller) KBOs is similar to brighter counterparts)

Cadence – 15 minute exposures, revisit each field three times separated by ~30-60 minutes

Wavelength Coverage – Need two NIR filters to get colors

George Rieke (UA), grieke@as.arizona.edu and John Stauffer (IPAC), stauffer@ipac.caltech.edu

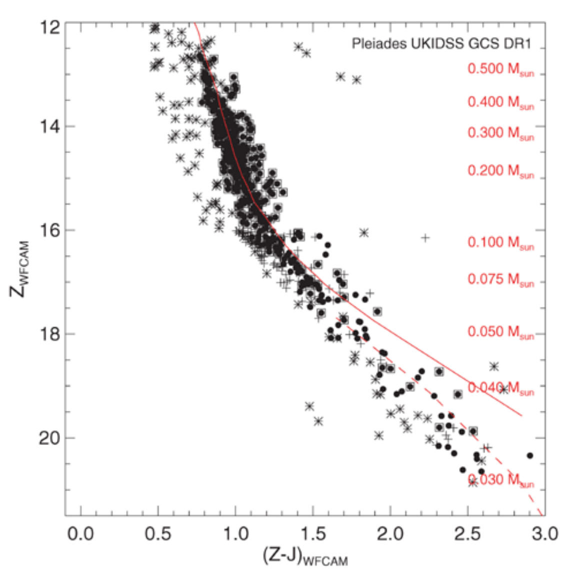
Extending Open Cluster and Star Forming Region IMFs to the Planetary Mass Regime

Background

The shape of the initial mass function contains within it many clues to the star-formation process. One particular topic of recent interest has been the shape of the IMF at very low masses. Are brown dwarfs formed in the same way as stars – or are they generally formed in circumstellar disks or hierachical binaries and ejected at young ages. What is the minimum mass object that can form in isolation – and what sets that mass? These questions are best answered by very deep surveys of nearby, young open clusters because dynamical evolution both preferentially ejects low mass cluster members and causes those that remain to be less well-concentrated to the cluster core. Current surveys and existing facilities cannot reach sufficient depths to answer these questions.

WFIRST

WFIRST will enable a uniform wide-field, deep, multi-epoch study of the nearest, young open clusters and star-forming regions (including clusters such as Pleiades, Alpha Per, IC2391/2602 and star-forming regions such as Taurus, Lupus, Sco-Cen and Chamaeleon). Even for the oldest of these clusters (the Pleiades, at 100 Myr), WFIRST can go deep enough to reach 5 M(Jup); for the youngest, WFIRST should be able to reach much lower in mass. In favorable cases, two epochs separated by 3-5 years will provide accurate enough proper motions to isolate cluster members. For other clusters, multiple epochs could be used to use variability (plus colors) to isolate cluster members. Comparison of empirical isochrones from these clusters of varying ages would then allow determination of evolutionary tracks for planetary mass objects. The spatial location of the lowest mass members relative to the stellar members would be used to constrain the physical mechanism for forming these free-floating planets.



Caption: Color-magnitude diagram for proper-motion selected stars and brown dwarf members of the Pleiades from the UKIDSS galactic cluster survey (Lodieu et al 2012, MNRAS). The solid and dashed lines are the 120 Myr Nextgen isochrone and the 120 Myr "Dusty" isochrone from the Lyon group.

Key Requirements

Depth – To below 10 M(Jup) at r ~ 175 pc – i.e. to K ~ 23 (5 sigma)
Field of View – Full cluster extent, regions of order 25-50 square degrees per cluster
Cadence – J and K band; two to three epochs (at least at K) separated by 3 or more years
Wavelength Coverage – Two NIR filters for color-magnitude diagram analysis

Lynne Hillenbrand (Caltech), lah@astro.caltech.edu

Stellar and Substellar Populations in Galactic Star Forming Regions

Background

Studies of low mass populations (encompassing stars, brown dwarfs, and even free-floating planetary mass objects) are hindered in star forming regions due to observational and astrophysical effects. These include: the large angular sizes of the nearby molecular clouds harboring newborn and young stellar objects, the significant extinction and reddening, and the excess emission due to accretion processes and circumstellar dust. Nevertheless, it is possible to disentangle the complexities of these effects with a combination of multi-color photometry and spectroscopy. For young stellar objects, Y-J is the best wavelength range for sampling the photospheric temperature and J-H and J-K colors are surface-gravity sensitive. Extinction, however, is degenerate with intrinsic near-infrared colors and therefore *spectroscopy is needed* in order to accurately de-redden observed colors and enable comparisons to predicted colors and magnitudes (or temperatures and luminosities). Science goals include extension of our knowledge of the initial mass function in young regions -- where the low mass objects are brighter by many orders of magnitude than they are on the main sequence -- down to and below the opacity limit for fragmentation within the molecular cloud. We see deeper into the mass function in these regions than anywhere else. What is the lowest mass object that can form like a star? How does the age distribution at 3 and 30 M_{JUP} compare to that for 0.3, and 3.0 M_{SUN} stars in the same cluster?

WFIRST

WFIRST will enable sensitive, systematic large-scale surveys of nearby star forming regions. These areas are typically hundreds of square degrees and have been completely surveyed before only by the shallow 2MASS and WISE. UKIDSS has provided increased depth but with limited (albeit wide-area) coverage. The next steps with WFIRST will enable probes of the substellar mass function to near its bottom, over the required wide areas. (JWST, by contrast, will have more depth but restricted spatial coverage). A unique capability of WFIRST will be its R=200 spectroscopy, whose potential is illustrated in the Figure.

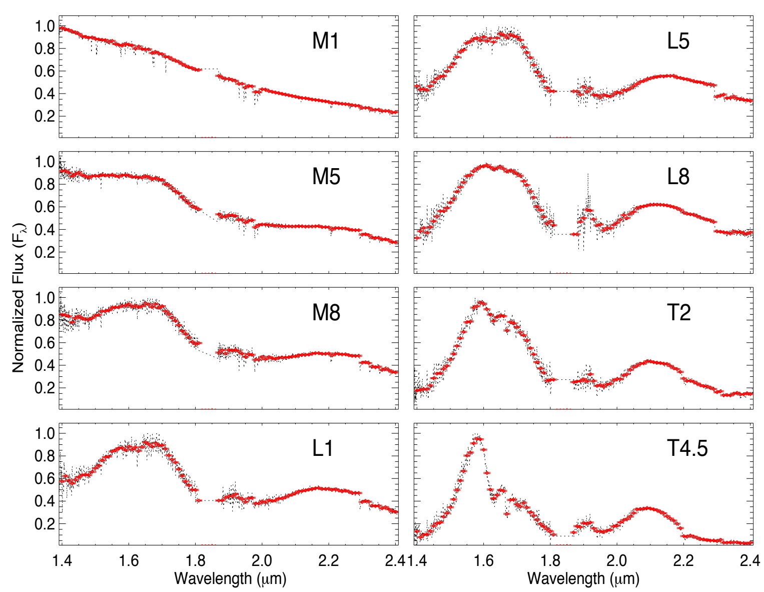
Key Requirements

- Large area surveys covering known star forming regions, with possible extension in to the galactic plane depending on confusion.

- Wavelength coverage beyond the H- opacity minimum, i.e. out to K-band. Photometry in all available filters.

- Grism spectroscopy. R = 200 is sufficient to spectral type M, L, and T-type objects probing temperatures below 1000K.

- Depth to M_H = 18 (15) to reache 1 (3) M_{JUP} at 1 Myr (Vega System).



Angelle Tanner (MSU), at876@msstate.edu

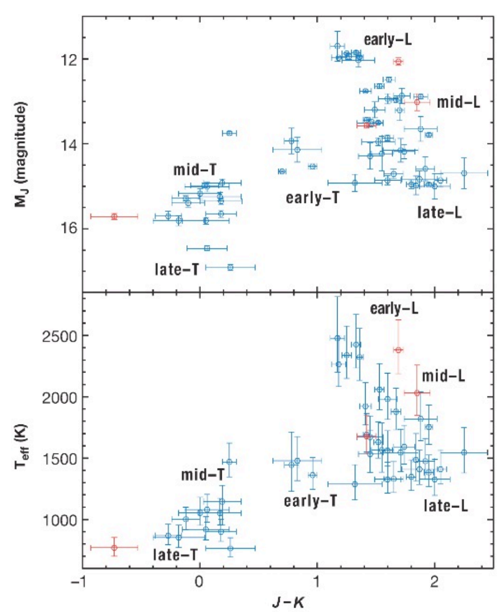
WFIRST: Additional Planet Finding Capabilities - Photometry

<u>Background</u>

One of the key scientific contributions of large infrared surveys like 2MASS, SDSS and WISE has been the detection of brown dwarfs, including record-setting cool Y dwarfs that are expected to be brown dwarfs with planetary masses. These surveys use infrared color information as well as proper motions to identify field brown dwarfs. While the number of field brown dwarfs is now in the hundreds and survey volumes are increasing, we know very little about the true number of brown dwarfs out to distances of 100 pc over the entire MLTY spectral range. This is essential information for the determination of the stellar mass function down through 0.1 $M_\odot$, into the brown dwarf and exoplanet mass regime. Measuring the stellar mass function over multiple orders of magnitude in mass and over a wide range of ages will allow us to better develop planet, brown dwarf and low-mass star formation models.

<u>WFIRST</u>

A focused infrared GO survey using at least three WFIRST filters has the potential to detect a few thousand L dwarfs and a few hundreds T dwarfs based on LSST expected performance and a smaller WFIRST field of view. The combination of LSST visual *rizy* and WFIRST NIR photometry will allow for a thorough census of brown dwarfs over the MLT spectral range, as LSST will be less sensitive to the cooler L dwarfs. A WFIRST brown dwarf photometric survey could be completed as a separate GO program as it would only require a couple deep (mag AB ~ 25) fields separated over a couple years for additional proper motion information independent from LSST. Some of the stars found with a LSST+WFIRST combined data set could have their parallaxes determined with the LSST data or with a focused infrared parallax programs. The brown dwarfs discovered from this survey could also be followed up with high-resolution infrared spectra from >10-m class telescopes to further constrain spectral types of the object and investigate multiplicity.



Caption: Near-infrared color-magnitude diagram of nearby brown dwarfs utilizing data from the 2MASS and other near-infrared surveys that have wavelength coverage (JHKs) similar to WFIRST (Kirkpatrick et al. 2005). A targeted WFIRST GO brown dwarf survey will go much deeper than 2MASS and, thus, will be able to extend the bounds of a complete a census of nearby MLT brown dwarfs.

<u>Key Requirements</u>

Coverage – > 2500 deg^2 high galactic latitude, > 1500 deg^2 galactic plane (HL survey)
Bands – Three of the four bands - F087, F111, F141, or F178
Sensitivity – Mag AB ~ 25

Jason Kalirai (STScI), jkalirai@stsci.edu

The Infrared Color-Magnitude Relation

Background

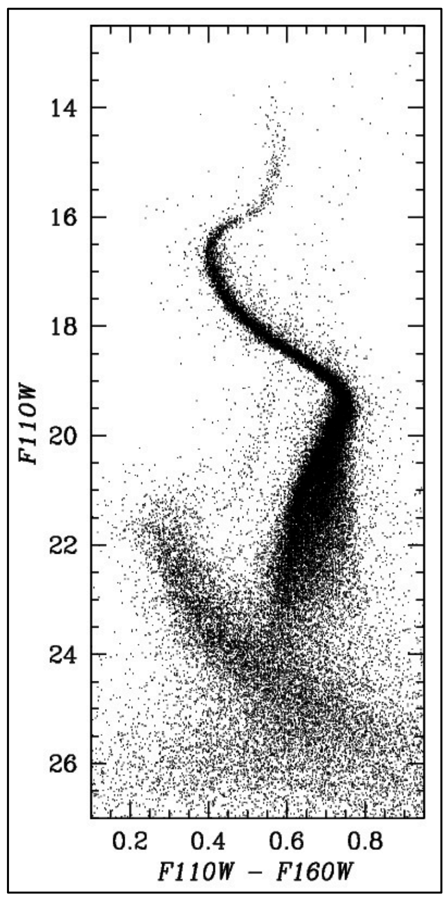
Star clusters in the Milky Way (MW) have served as the primary tools to measure the color-magnitude relation of stars, and to calibrate its dependency on stellar properties such as age and metallicity. This relation is a key input to test stellar evolution models, and in turn to carry out population synthesis studies that aim to interpret the integrated light of astrophysical sources across the Universe (e.g., Bruzual & Charlot 2003). For decades, this work has primarily focused on the interpretation of visible-light color-magnitude diagrams (CMDs).

WFIRST

WFIRST will enable high-precision IR CMDs of stellar populations. The figure below illustrates the morphology of the IR CMD of the globular cluster 47 Tuc, from a 3 orbit (depth) exposure with the WFC3/IR camera on HST (Kalirai et al. 2012). The sharp "kink" on the lower main sequence is caused by collisionally induced absorption of H_2. Unlike the visible CMD, the inversion of the sequence below the kink is orthogonal to the effects of distance and reddening, and therefore degeneracies in fitting fundamental properties for the population are largely lifted. The location of the kink on the CMD is also not age-sensitive, and therefore can be used to efficiently flag 0.5 Msun dwarfs along any Galactic sightline with low extinction. A WFIRST two-stage survey will first establish the IR color-magnitude relation and the dependency of the "kink" on metallicity through high-resolution, deep imaging of Galactic star clusters. Second, this relation can be applied to field studies to characterize the stellar mass function along different sightlines, the dependency of the mass function on environment, and to push to near the hydrogen burning limit in stellar populations out to 10's of kpc.

Key Requirements

Depth – Well dithered exposures extending down to the H burning limit in clusters with [Fe/H] = -2.2 to 0.0 (i.e., 10 kpc)
Field of View #1 – Single pointings for globular clusters covering appreciable spatial extent
Field of View #2 – Wide field survey of Galactic plane sampling over star forming regions and spiral arms
Cadence – One image per galaxy
Wavelength Coverage – Two NIR filters for color-magnitude diagram analysis



Caption: IR color-magnitude diagram for the nearby globular cluster 47 Tuc, constructed from a 3 orbit (depth) observation with HST/WFC3/IR (Kalirai et al. 2012). The kink in the lower main-sequence of the cluster is caused by H_2 opacity. The fainter main-sequence represents stars from the background SMC galaxy.

John Stauffer (IPAC), stauffer@ipac.caltech.edu

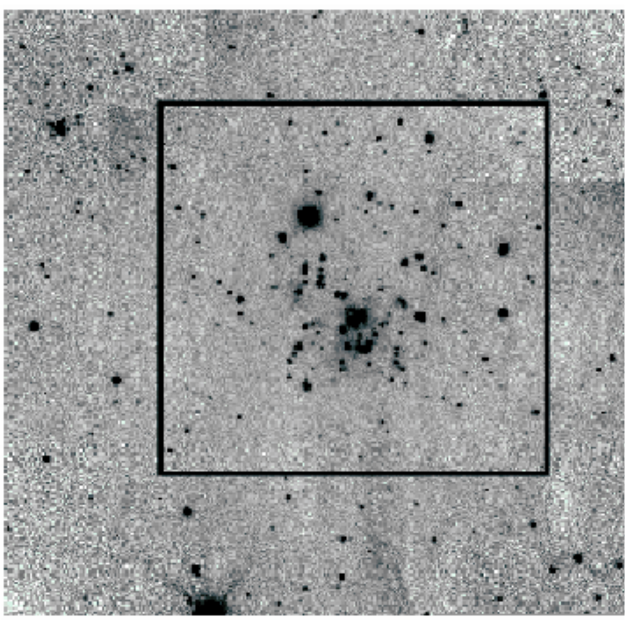
The Most Distant Star-Forming Regions in the Milky Way

Background

Wide field imaging surveys of nearby spiral galaxies allow us to study how the star-formation process depends on global properties (Fe/H, mean gas surface density, disk kinematics). By their nature, those studies are limited in their abilities due to the distance of the target galaxies from the Earth. Similar studies in the Milky Way could do much better, but are limited by interstellar extinction and confusion. A space-based near-IR survey of the outer galaxy can overcome many of these problems and allow use of the Milky Way as a laboratory for how the star-formation process depends on metallicity, gas surface density and triggering mechanisms. The most distant star-forming regions in the galaxy are expected to have [Fe/H] ~ -1.0 (Brand et al 2003) – comparison of the IMF of such clusters to those in the inner galaxy could help interpret colors of high redshift galaxies where low metallicities are also expected.

WFIRST

The expected edge of the star-forming disk of the Milky Way is at of order R(G) ~ 20 kpc, or about 12 kpc distant from Earth. Towards the outer-galaxy where confusion is much reduced, a WFIRST JHK survey is capable of reaching stars down to 0.1 Msun at 1 Myr at 12 kpc. Two-color J-H, H-K diagrams can then be used to identify YSOs with warm, dusty circumstellar disks. Multi-epoch imaging of candidate clusters can further identify additional members by their variability. A single epoch survey of the entirety of quadrants 2 and 3 of the disk over +/- one degree in latitude could be accomplished in less than a month of observing time with WFIRST. Alternatively, the same amount of time could be used to sample a smaller longitude range but wider latitude range (to account for larger gas scale height and disk warp at large galactocentric distance).



Caption: Near-IR image of the star-forming region WB89-719, aka IRAS 06145+1455, the most distant known star-forming region at R(G) ~ 20.2 kpc (Brand and Westerloot 2007, AA 464, 909).

Key Requirements

Depth – To below 0.1 M(sun) at R(G) = 20 kpc, or to K ~ 19 (5 sigma)
Field of View – The outer MW plane – 90 < l < 270, -1 < b < 1
Cadence – One epoch all bands; multiple epochs on specific regions
Wavelength Coverage – JHK filters for color-color and CMD analysis

Daniel Stern (JPL), daniel.k.stern@jpl.nasa.gov

Quasars as a Reference Frame for Proper Motion Studies

Background

Luminous quasars behind the Magellanic Clouds or the Galactic bulge provide several unique and important scientific applications. First, they provide the best reference frame for proper motion studies (e.g., Kallivayalil et al. 2006a,b; Piatek et al. 2008). For example, recent improvements measuring the proper motion of the Magellanic Clouds all relied on Hubble observations of fields centered on quasars. The results were surprising, as the Clouds were found to be moving significantly faster than previous estimates (e.g., van der Marel et al. 2002). The tangential motion of the SMC was also found to differ from that of the LMC. This implies that the Clouds may not be bound to each other or the Galaxy, and may instead be on their first pericentric passage. Precisely measuring the proper motion of the Magallanic Clouds will also improve modeling of the Magellanic Stream, which is a sensitive probe of the Galactic potential. Finally, bright background quasars are useful background probes for absorption studies of the interstellar medium.

WFIRST

The deep, wide-field, high-resolution imaging capabilities of WFIRST will provide a significant improvement for this science, vastly improving the statistics relative to previous Hubble studies. The precise astrometry afforded by space-based observations, combined with the large number of background AGN identified from their broad-band spectral energy distributions (SEDs), including mid-IR data (e.g., Kozlowski et al. 2011, 2012), will allow large numbers of both AGN and Galactic/Magellanic Cloud stars to be identified in each field.

Key Requirements

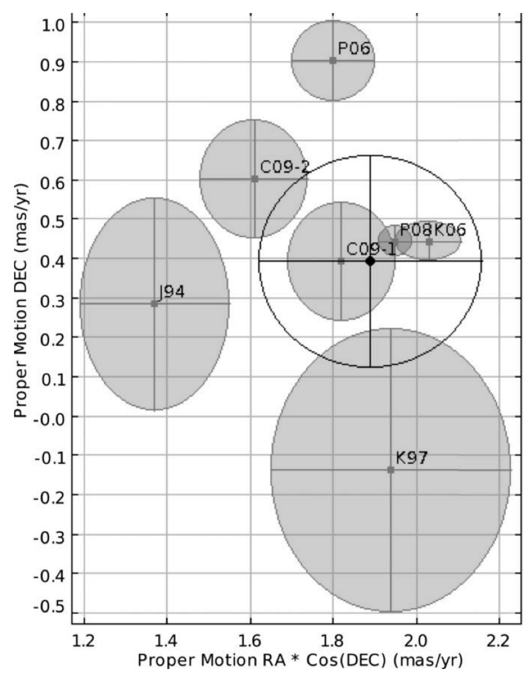
Depth – To provide high S/N detections of large numbers of AGN

Morphology – To precisely measure quasar positions

Grism – For spectroscopic confirmation of quasar candidates

Field of View – Wide-area to improve statistics

Wavelength Coverage – single band sufficient



Caption: Recent measurements of the proper motion of the Large Magellanic Clouds, from Vieira et al. (2010).

WFIRST Guest Investigator (GI) and General Observer (GO) Science Cases

Scott Gaudi (OSU), gaudi@astronomy.ohio-state.edu

Proper Motions and Parallaxes of Disk and Bulge Stars

Background

Measurements of the kinematics and three-dimensional structure of stars in the Galactic Bulge and inner disk allow for the determination of the dynamical mass in these populations, and provide important clues to their formation and evolutionary history. The dominant formation mechanism of bulges in the universe (i.e., secularly-grown pseudobulges versus merger-driven classical bulges) remains poorly understood (i.e., Kormendy & Kennicutt 2004), and our bulge provides the nearest and thus most accessible example with which to test the predictions of various formation models. Nevertheless, there are a number of challenges to obtaining such measurements for the bulge, in particular the small proper motions and parallaxes, and the large and variable extinction towards the bulge. To date, information on the kinematics of bulge stars has been limited to primarily radial velocities, luminous stars or stars with large proper motions, and a few pencil-beam surveys. Direct geometrical distances to individual stars in the bulge have been essentially unavailable.

WFIRST

WFIRST will enable high-precision proper motion measurements and rough parallaxes to essentially all the ~3×10^8 bulge and foreground disk stars in the microlensing survey FOV with magnitudes of J<19. For the exoplanet survey, WFIRST will achieve a SNR~10 per observation for stars with J<19. Assuming an astrometric precision of a σ_{AST} ~ mas per observation (i.e., σ_{AST} ~ FWHM/SNR~0.2"/100~mas), and N~10^4 observations, the final mission uncertainty on the measured proper motions over a T~4 year baseline will be

σ_{μ}~ sqrt(12/N)*(σ_{AST}/T) ~ 0.01 mas/yr.

The typical proper motion of a star in the bulge is μ~100 km/s/(8000 pc) ~ 3 mas/year, and thus individual stellar proper motions will be measured to ~0.3%. Similarly, the fractional uncertainty on the parallax of a star in the bulge will be

σ_pi/Pi ~ σ $_{\_AST}$/Pi/sqrt(2N) ~ 10%

where Pi ~ 1/8 mas is the typical parallax of a star in the bulge. Because these observations will be taken in the NIR, they will reach below the bulge MS turnoff and will be relatively unaffected by extinction. The occasional observations in bluer filters will help distinguish between bulge and disk populations. WFIRST will provide unprecedented measurements of the kinematics and structure of the bulge.

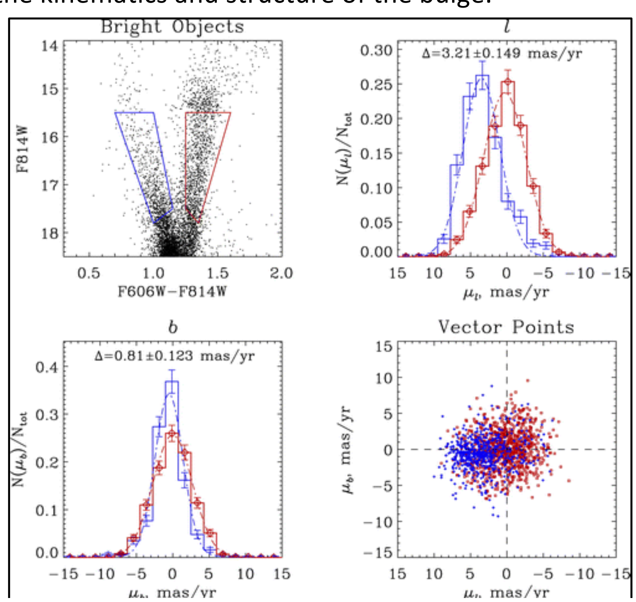
Key Requirements

Total Span of Observations –T~ 4 years

Total number of epochs - ~10^4

Astrometric precision per epoch for J<19 ~ mas

Kormendy & Kennicutt 2004, ARAA, 42, 603



Caption: CMD and bulge, disk proper motion distributions from an HST study using ASC/WFC (Clarkson et al 2008, ApJ, 684, 1110). WFIRST will provide individual proper motions with ten times smaller uncertainties than HST.

Jason Kalirai (STScI), jkalirai@stsci.edu

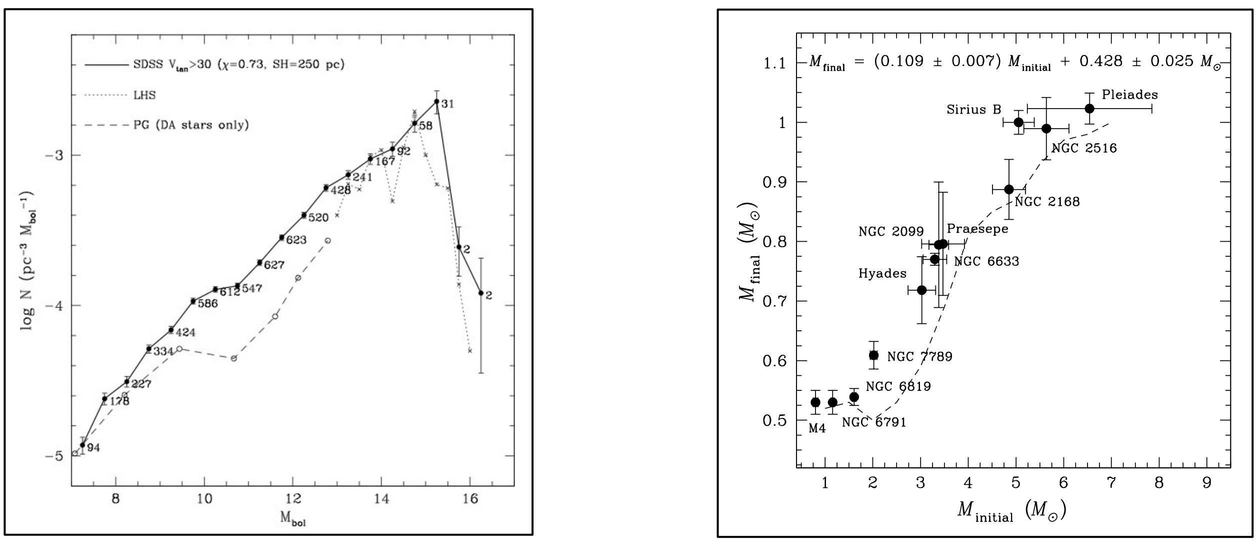
Stellar Fossils in the Milky Way

Background

98% of all stars will end their lives quiescently and form white dwarfs. These remnants are remarkably simple as they contain no nuclear energy sources. Over time, white dwarfs will radiate away thermal energy and cool, thereby becoming dimmer and redder. In old stellar populations, such as the Galactic halo, a significant fraction of the mass is now tied up in white dwarfs and the properties of these stars hold clues to infer the nature (i.e., the age and mass function) of their progenitors.

WFIRST

The largest sample of white dwarfs studied to date comes from the SDSS, which has increased the known population to over 20,000 remnants (Eisenstein et al. 2006). The brightest white dwarfs have M_V = 10, therefore SDSS is mostly sensitive to the luminosity function out to less than a 1 kpc. WFIRST will discover and characterize the luminosity function of white dwarfs down to a much larger volume, across different sightlines. In the Galactic disk, the spatially-dependent structure of these luminosity functions correlates to peaks in the star formation history (see Figure below). The faintest stars, also in the Galactic halo, provide a robust estimate of the formation time of the first populations (Harris et al. 2006). Follow up spectroscopy of these stars can yield their fundamental properties (temperature, gravity, and mass), which can be connected to the progenitor masses through the well-measured initial-final mass relation (Kalirai et al. 2008). A wide field survey of the Milky Way disk and halo will provide a complete characterization of this remnant population in the Milky Way.



Caption: The luminosity function of white dwarfs in the Galactic disk (Harris et al. 2006) shows a turnover at the faint end (left), corresponding to the age of the oldest stars in the Galactic disk. The initial-final mass relation of stars is shown in the right panel (Kalirai et al. 2008).

Key Requirements

Depth – Measure faintest white dwarfs in the local halo (M_V = 17).

Field of View – Sample range of stellar environments in Galactic disk and different probes in halo.

Cadence – Second epoch for proper motions would enable kinematic separation of components and a much cleaner selection from contaminants.

Wavelength Coverage – Two NIR filters for color-magnitude diagram analysis

Angelle Tanner (MSU), at876@msstate.edu
David Bennett (U Notre Dame)

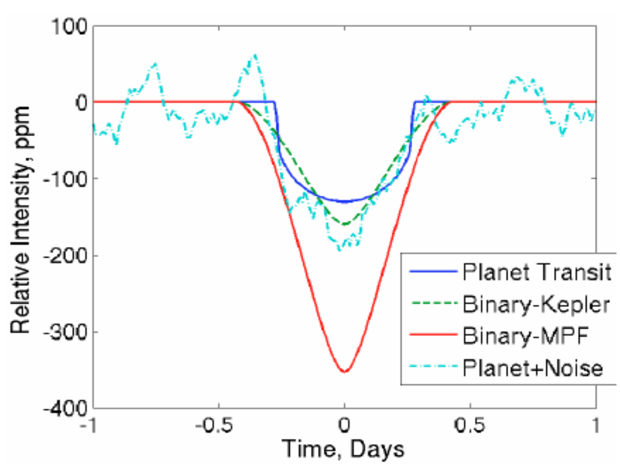
WFIRST: Additional Planet Finding Capabilities - Transits

Background

Since the detection of the first transiting planet, HD209458, in 2000 over 200 planets have been detected with this method. The recently extended Kepler mission will eventually open the flood gates of such systems with over 2000 planetary candidates. The goal of the Kepler mission is to detect habitable earth-mass planets around solar-type stars and it is close to that goal. An advantage to the detection of a transiting planet is that we are able to place stringent limits on the mass and radius of the planet, thus determining its density. Finding transiting planets also allows us to study the atmospheric composition of hot Jupiters and super-Earths through transit spectroscopy and photometry.

WFIRST

The primary objective of the WFIRST exoplanet science program is to complete the statistical census of planetary systems in the Galaxy with a microlensing survey. This program will cover 500 days of observation time over five years and is expected to be sensitive to habitable Earth-mass planets, free floating planets and all solar system analog planets except Mercury. Using estimates of the anticipated signal-to-noise of the data as well as the observing cadence and number of stars in the microlensing study, It is expected that WFIRST will obtain light curves with this cadence for ~$3X10^8$ stars and a photometric precision of 1%. With this sensitivity and observing cadence the WFIRST microlensing light curves can also be used to detect up to 50,000 Jupiter transits around main sequence stars and about 20 super-Earth transits around the brightest M dwarfs in the field of view. The statistics on the populations of hot Jupiters from the jovian transits will shed light on the mechanisms responsible for planetary migration when combined with information on the properties of the host star.



Caption: Simulated planetary transit light curve from the Microlensing Planet Finder mission (light blue, noise added) similar to WFIRST (Bennett et al. 2010) compared to Kepler (Borucki et al. 2010).

Key Requirements

Duration – 500 days (μL survey)
Precision – 1% photometry
Cadence – Every 15 minutes
Sensitivity – J < 19 at 5 sigma
S/N – ~100 for all 300 transits of a Jupiter mass planet in a 3 day orbit

Angelle Tanner (MSU), at876@msstate.edu

WFIRST: Additional Planet Finding Capabilities - Astrometry

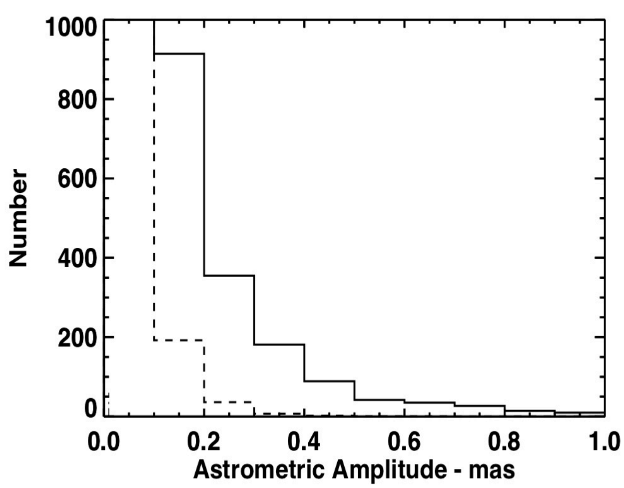
Background

While the first exoplanet discovered solely through astrometric observations remains elusive, this method of exoplanet detection has been used to confirm their existence and determine the mass of the planet. While not all planets transit their star, they do all make them wobble. It is just a matter of getting a large number of data points with good astrometric precision. For instance, the $0.64M_J$sini Jupiter mass planet discovered around the M dwarf GJ 832 at an orbital separation of 3.4 AU, period of 9.35 years and distance of 5 parsecs should produce an astrometric wobble with about a 1 milli-arcsecond amplitude.

WFIRST

The primary objective of the WFIRST exoplanet science program is to complete the statistical census of planetary systems in the Galaxy with a microlensing survey that will cover 500 days of observation time over five years. In order to maximize the number of microlensing events, WFIRST will observe a set of adjacent fields in the Galactic bulge. Observing in the near infrared significantly reduces the effects of extinction relative to visible wavelengths, increasing the number and apparent brightness of the background stars. A total of seven fields will be observed. The exposure time will be 88 seconds per field, with a slew and settle time of 38 seconds between fields. With this observing cadence and WFIRST's 0.5" spatial resolution, the positions of the ~$3X10^8$ stars collected for the microlensing survey can also be used to detect hundreds of > 10 M_J planets in 100 day orbits around 0.05 – 0.3 $M_¤$ M dwarfs. While the astrometric precision of a single observation may be on the order of 2.5 milli-arcseconds, WFIRST will collect a few thousand observations over the course of the microlensing program.

Caption: The astrometric signals of 10 M_J (dashed) and 40 M_J (solid) companions in a 100 day orbit around 10% of the 28000 M dwarfs in the FOV. With > 20000 observations, final astrometric precisions will be < 0.05 mas



Key Requirements

Duration – 500 days (µL survey)

Resolution – 0.5"

S/N – 100 for a J < 19 mag star

Precision – 2.5 mas single measurement

Roeland van der Marel and Jason Kalirai (STScI), marel@stsci.edu; jkalirai@stsci.edu

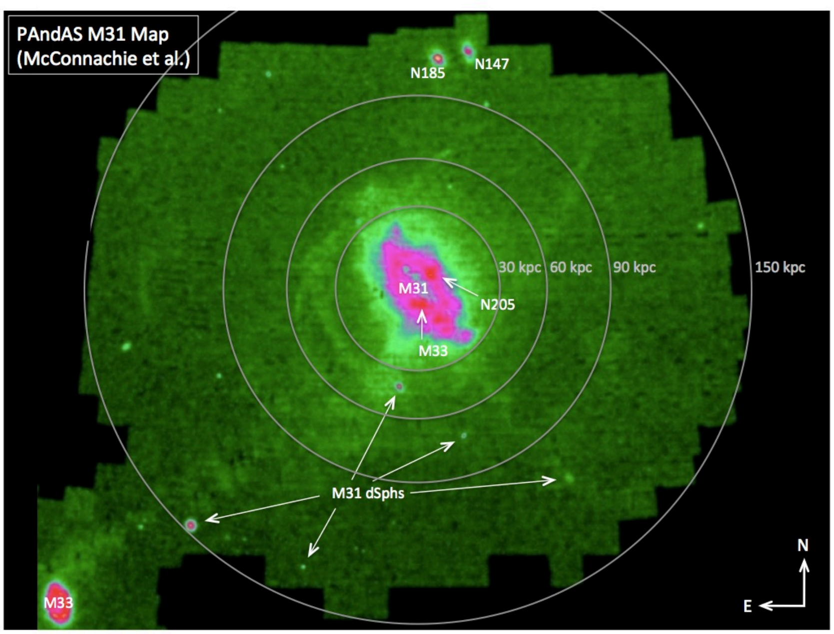
Dissecting Nearby Galaxies

Background

Recent wide-field imaging surveys of the Milky Way and M31 (Juric et al. 2008; McConnachie et al. 2009) have enabled a new landscape to test cosmological models of galaxy formation on small scales (Bullock & Johnson 2005). Direct imaging of stellar halos can provide detailed insights on the surface brightness profile, chemical abundance gradients, stellar ages, level of substructure, and quantity of dwarf satellites and star clusters. This input represents a key constraint to unravel the formation and assembly history of galaxies within the hierarchical paradigm (Font et al. 2011), but is limited to the detailed study of just two fully resolved spiral galaxy halos. Current surveys of galaxies outside the Local Group (Spitzer/SINGS, HST/ANGST) have primarily involved either deep pencil-beam probes of narrow fields of view, or wide-field coverage at shallow depth. Similarly, optical ground-based surveys such as SDSS and Pan-Starrs lack the depth to study the tracer population, red giant branch stars, outside the Local Group.

WFIRST

WFIRST will enable a uniform 1.) wide-field, 2.) deep, and 3.) high-resolution study of the full extent of over a hundred nearby galaxies in the Local Volume. Accurate photometric characterization of the top three magnitudes of the red giant branch in each galaxy can map the halo structure, surface brightness profile, substructure content, and metallicity gradient. Variations in these properties, and their connection with the host environment and galaxy luminosity will provide tight constraints to cold dark matter models of galaxy formation.



Caption: A (very) wide-field map of M31 from the PAndAS survey (McConnachie et al. 2009) reveals the clearest picture of substructure in a spiral galaxy's halo.

Key Requirements

Depth – Several magnitudes of the red giant branch in ~100 galaxies (i.e., out to d = 5 Mpc)
Field of View – Full halo extent out to 150 kpc (tiling in nearby galaxies)
Cadence – One image per galaxy
Wavelength Coverage – Two NIR filters for color-magnitude diagram analysis

Christopher J. Conselice (Nottingham), conselice@nottingham.ac.uk

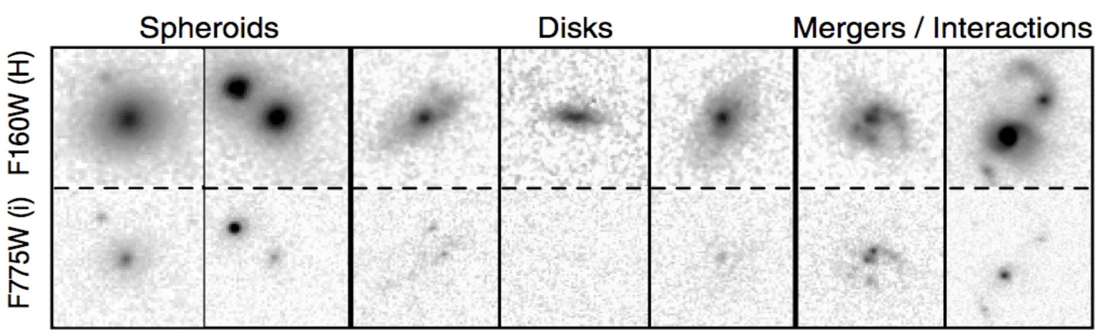
Galaxy Structure and Morphology

Introduction

There are several major issues within galaxy formation and evolution where WFIRST will make a big impact. One of these critical aspects of WFIRST will be to study galaxy structure - i.e., sizes and morphologies of galaxies on a larger area than is possible with Hubble Space Telescope, or from the ground using adaptive optics. Galaxy structure is critical for deciphering the processes which drive galaxy assembly and allow us to move beyond simply counting properties of galaxies to study directly their assembly processes through e.g., mergers, gas accretion, and star formation. Yet this has proved difficult to do for galaxies at $z > 1$. Properties such as the asymmetry of a galaxy's light, its concentration, and the clumpy nature of this light all reveal important clues to the galaxy formation process.

WFIRST

The Hubble Space Telescope has shown how powerful this resolved structural approach is for understanding galaxies. Only very small fields have been observed with Hubble, and most of those within the observed optical. To study the formation of galaxies will require high resolution imaging in the near-infrared, which WFIRST will provide. Large area surveys of at least a few degrees will be much larger than any near infrared survey of this type for distant galaxies yet performed. This will allow us to directly measure in an empirical way how galaxies, and the stars within them, assembled over most of cosmic history to within a Billion years of the big bang.



Caption: How infrared light (F160W) shows features of distant galaxies not seen in optical light (F775W) (from Kocevski et al. 2011)

Key Requirements

Depth – Deep enough to examine galaxy structure down to ⅕ L* up to z = 3

FoV – Large survey areas to obtain statistically representative galaxy populations

Wavelength – Need > 1.6 microns to examine the rest-frame optical structures of galaxies

Megan Donahue (Michigan State University), donahue@pa.msu.edu

The Evolution of Massive Galaxies: the Formation and Morphologies of Red Sequence Galaxies

Background

The most massive galaxies in the present day universe are red, usually dormant, elliptical galaxies. They appear in the color-magnitude diagrams of galaxies in clusters of galaxies as the red sequence (RS). The red sequence represents a distinct population of galaxies whose stars formed at high redshift (z>3) and have passively evolved since then. These galaxies also experience significant interactions and mergers over their lifetime. The red sequence feature is so prominent that it can be used to discover distant clusters of galaxies and to estimate their redshifts. Current studies suggest that while the stars in these galaxies formed early, the assembly of the galaxies we see locally occurred relatively late. Studies of the RS galaxies as a function of redshift, cluster mass, and local environment are critical tests of our understanding of galaxy evolution.

WFIRST

WFIRST will enable sensitive IR color-magnitude diagrams of RS galaxies in clusters and in the field at redshifts representing the epoch at which the red sequence is beginning to assemble, z~1.5-2.5. The spatial resolution will allow galaxy sizes to be estimated; as mergers progress, the stellar orbits get progressively more puffed out. The best photometric redshifts will be obtained from filters which span the 4000 Angstrom break and which are medium-width (not too broad, see FourStar results from Spitler et al. 2012.)

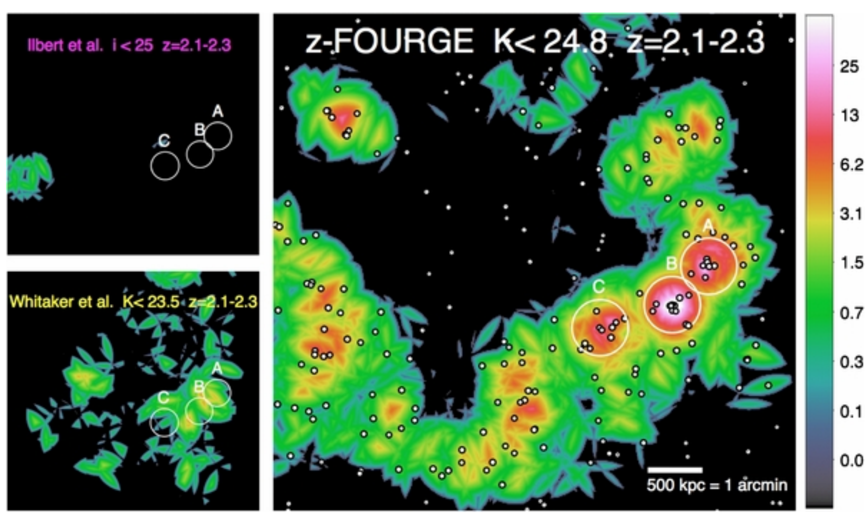
Key Requirements

Depth – Well dithered exposures sensitive to K~25-26 (AB)

Field of View – Targeted follow-up of high-z candidates (from Sunyaev-Zeldovich surveys or other techniques). Cluster size is ~ 1-2 arcmin, ~ independent of z.

Field of View – Survey for z=1.5-2.5 clusters: ~ 100 sq degrees would include ~20 clusters at M~10^14 h^-1 solar masses if you had to find the clusters first.

Wavelength Coverage – Medium-band NIR filters.



Caption: Nearest-neighbor surface density maps for z = 2.1-2.3 in a 9' × 9' region in the COSMOS field (Spitzer et al. 2012).

Chris Mihos and Paul Harding (Case Western), mihos@case.edu; paul.harding@case.edu

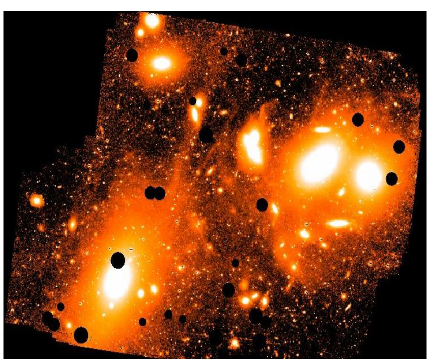
Deep Surface Photometry of Galaxies and Galaxy Clusters

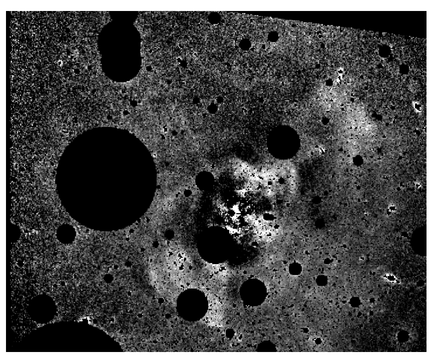
Background

The low surface brightness outskirts of galaxies hold a wealth of information about processes driving their evolution. Interactions and accretion events in galaxies leave behind faint, long-lived tidal tails and stellar streams which can be used to trace their interaction history (e.g., Martinez-Delgado et al 2010). In galaxy clusters, tidally stripped material mixes to form the diffuse intracluster light (ICL; e.g., Mihos et al 2005), whose structure and luminosity provides constraints on the dynamical history of the cluster (Rudick et al 2009). The photometric properties of the extended disks of spiral galaxies probe star formation in low-density environments (e.g., Bigiel et al 2010), as well as dynamical models for stellar migration in galaxy disks (Sellwood & Binney 2002; Roskar et al 2008). However, accessing this information is quite difficult, as optical surface photometry must reach $\mu_V > 27$, or < 1% of the ground-based night sky. Working to an equivalent depth in the near IR is impossible from the ground, since the IR sky is much brighter and significantly more variable than in the optical. Furthermore, this level of accuracy must be achieved over a wide field of view (>0.5 degree) to study nearby galaxies and clusters.

WFIRST

WFIRST can take advantage of the low IR background levels from space to deliver deep, wide-field surface photometry in the near IR. Compared to optical surface photometry, working in the IR has the advantage of maximizing the signal from the old stellar populations that comprise the ICL, providing a more direct tracer of stellar mass at low surface brightness, and minimizing the effects of scattered light from Milky Way galactic cirrus and internal extinction from the target galaxies. An off-axis design and use of a pupil mask would reduce contamination from stray light and provide a stable, simple PSF which is critical for the subtraction of extended stellar wings in deep imaging. The resulting images will be a boon to the study of dynamical evolution, star formation processes, and stellar populations in the outskirts of nearby galaxies and galaxy clusters.





Left – Deep imaging of diffuse ICL in the Virgo Cluster (Mihos et al 2005), showing tidal streams and extended galaxy halos. The image covers 2.5 deg^2 to a limiting depth of $\mu_V = 28.5$.

Right – The Virgo elliptical galaxy M49, after subtraction of smooth light profile, showing a complex system of diffuse tidal shells from a recent accretion event (Janowiecki et al 2010).

Key Requirements

Depth – Limiting J-band surface brightness of ~ 27 mag/arcsec^2 (~ 0.001 MJy/sr).
FOV – Wide field necessary to cover nearby galaxies and galaxy clusters with a minimum of tiling.
Low scattered light – Off-axis design and pupil mask would limit contamination from stray light.
PSF stability – PSF stability on large scales necessary for proper subtraction of stellar wings.
Wavelength – IR needed to sample peak of old population SED, better trace stellar mass distribution, and minimize contamination due to scattering and absorption from Galactic and target galaxy dust

Megan Donahue and Mark Voit (Michigan State University), donahue@pa.msu.edu

Finding and Weighing Distant, High Mass Clusters of Galaxies

Background

The mean density of matter and dark energy and the initial fluctuation spectrum determine the abundance and growth of clusters of galaxies (e.g Voit 2005). The most dramatic effects are experienced by the abundance of the most massive clusters. Furthermore, the abundance of the most extremely massive clusters tests the assumption of Gaussianity of the power spectrum at Mpc scales. The key to cluster cosmology lies in accurate estimates of both the number counts (as a function of redshift) and the gravitating masses of clusters of galaxies. Finding clusters by their projected lensing mass, by the overdensity of red sequence galaxies, and by their Sunyaev-Zeldovich decrement on the CMB would provide mutual verification of cluster existence, hot gas (baryonic) content, presence of a prominent red sequence. Spitzer IRAC surveys have discovered over one hundred z>1 candidates in 7.25 sq degrees (Eisenhardt et al. 2008), yielding at least one massive cluster at z=1.75 (Brodwin et al. 2012; Stanford et al. 2012).

WFIRST

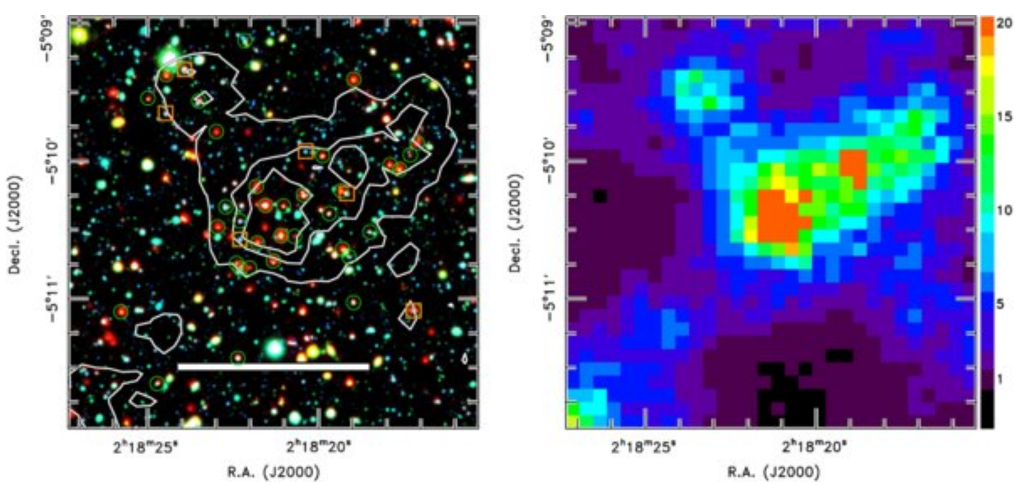
Survey fields obtained for WFIRST weak lensing shear and/or baryon acoustic oscillation studies will also allow a census of massive clusters. Photometric redshift observations, either ground-based or from WFIRST, would be required to estimate the redshift of newly discovered clusters.

Key Requirements

Depth – Well-dithered exposures sufficient to obtain shape measurements for galaxies at z>z_cluster; shape measurements benefit from 3-4 repeats **[This section needs galaxy density per sq arcmin as a function of z and magnitude limit.]**

Field of View – A wide-field survey of 8300 sq degrees include 100 10^14 h^-1 and 2800 10^13.7 h^-1 z=2-2.5 clusters; for z=1.5-2.0, the numbers rise to 1660 and 20,000 clusters for the same masses, respectively; the most massive clusters are the most rare, the larger the survey, the better the probe of the high-sigma tail of the mass distribution

Wavelength Coverage – NIR filters



Caption: Left panel shows a false-color image of a Spitzer-selected cluster at z=1.6 (Papovich et al. 2010). Blue corresponds to the Suprime-Cam B band, green to the Suprime-Cam i band, and red to the Spitzer 4.5 µm band. The right panel shows the surface density of galaxies, color coded in units of standard deviations above the mean.

Daniel Stern (JPL), daniel.k.stern@jpl.nasa.gov

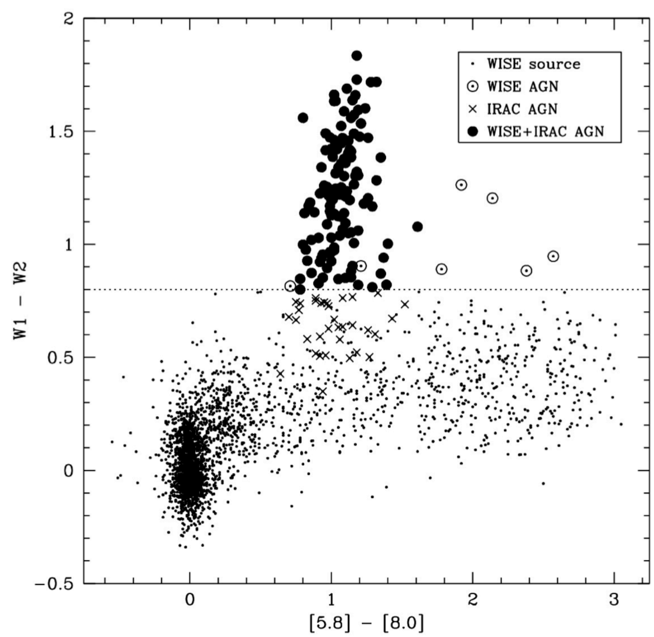
Obscured Quasars

Background

Obscured, or type-2 quasars are expected to outnumber unobscured, type-1 quasars by factors of 2-3. They are predicted by models of active galactic nuclei (AGN), and are required to explain the hard spectrum of the cosmic X-ray background. Until recently, however, our census of this dominant population of AGN has been lacking since such systems are difficult to identify in optical and low-energy X-ray surveys. High-energy missions to date have had limited sensitivity, while the soon-to-be-launched NuSTAR mission has a very limited field-of-view. Mid-infrared surveys, initially with Spitzer (e.g., Lacy et al. 2004; Stern et al. 2005) and more recently with WISE (Stern et al. 2012) have dramatically changed the situation. WISE identifies 62 AGN candidates per deg2 with an expected reliability in excess of 95%. The mid-infrared depth considered, 160 uJy at 4.6 um, corresponds to *i*~19.8 for a typical type-1 quasar. At this depth, only ~20 type-1, unobscured quasars are expected per deg2 (Richards et al. 2006), implying that WISE has finally realized the efficient identification of the dominant luminous AGN population across the full sky.

WFIRST

While mid-infrared observations with WISE have identified this dominant population of obscured, luminous quasars, WFIRST will be required to characterize its properties. Working with deep ground-based optical data, WFIRST will provide photometric redshifts for this population, something not possible from the mid-infrared data alone since the identification relies on the power-law mid-infrared spectra of luminous AGN. Photometric redshifts will allow us to probe the cosmic history of obscured black hole growth, and relate it to galaxy formation and evolution. AGN feedback is expected to play an important role shaping the present-day appearances of galaxies. Measuring the clustering amplitude of obscured and unobscured quasars will probe AGN unification scenarios. For the classic orientation-driven torus model, clustering should be the same for both populations. On the other hand, if obscured AGN are more common in merging systems, with the obscuration caused by galactic-scale material, then the clustering amplitudes are expected to differ.



Caption: Mid-infrared color-color diagram, illustrating that a simple WISE color cut of W1-W2 ≥0.8 identifies 62 AGN per deg2 with 95% reliability assuming the complete reliability of the Stern et al. (2005) Spitzer AGN selection criteria. From Stern et al. (2012).

Key Requirements

Depth – Provide robust photometric redshifts for sub-L* populations to z~2
Field of View – Wide-area surveys required for clustering analysis
Wavelength Coverage – >2 NIR filters for robust photometric redshifts

Xiaohui Fan (University of Arizona), fan@as.arizona.edu

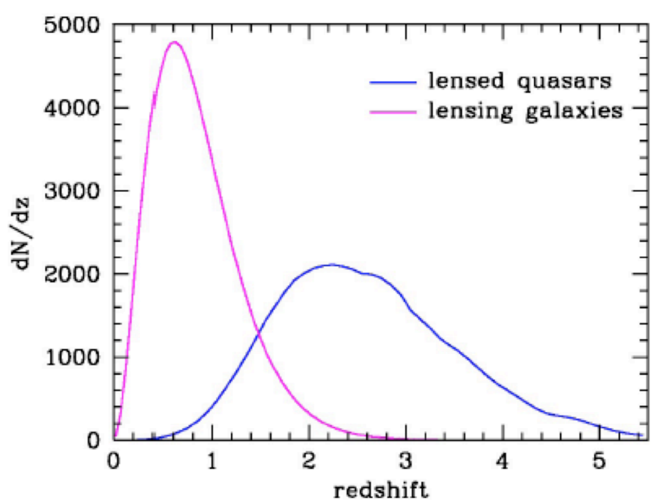
Strongly Lensed Quasars

Background

Strong gravitational lensing, when multiple images of distant objects are produced by massive objects in the foreground, is a powerful and unique tool for both cosmology and galaxy/AGN physics (e.g., Oguri et al. 2012). Applications of strongly lensed quasars include: using time delay among different lens components to measure H_0 and to constrain the expansion history of the Universe (Fassnacht et al. 2002); using lens models to measure galaxy mass and structure (Bolton et al. 2006); using flux ratio anomalies to probe dark matter halo properties and the existence of halo subtracture (Keeton et al. 2006); using AGN microlensing to probe accretion disk structure (Kochanek et al. 2006); using the quasar lensing fraction to study magnification bias and the quasar luminosity function (Richards et al. 2006); using high spatial resolution imaging of lensed systems to study properties of quasar host galaxies and environments (Peng et al. 2006); using rare examples of quasars acting as gravitational lenses to study the cosmic history of the black hole-bulge relation (Courbin et al. 2012). However, strong lensing is a rare event, requiring wide-field, high resolution imaging to establish a large sample for statistical studies, and to uncover those with ideal lensing configurations for cosmological tests (so-called "Golden Lenses").

WFIRST

The deep, wide-field imaging data from WFIRST surveys will provide a treasure trove for lensing studies. With a pixel size of ~0.2", WFIRST will resolve any multiply imaged system with separation >0.4". This is expected to account for more than half of all strong quasar lenses, and will allow accurate photometry of lensed image components as well as lensing galaxies. Multicolor photometry will provide accurate photometric redshifts for sources and lenses. Figure 1 presents the expected number/redshift distributions of lensing galaxies (lenses) and lensed quasars (sources) in a total survey area of 20,000 deg, with a limiting magnitude of ~24 AB and image separation of >0.5". This represents a nearly two orders of magnitude increase in size from current samples (Inada et al. 2012). Strong lensing is also one of the key areas for LSST science. WFIRST will have strong synergy with LSST, providing deeper imaging with higher spatial resolution and more accurate photometry and photometric redshifts.



Key Requirements

Depth – To sample a wide range of quasar luminosity and to detect faint lensed image components
Spatial Resolution – This is the key: a pixel size and resolution <0.3" is needed to uncover the majority of lenses and to allow accurate photometry of lensed components
Field of View – Wide-area surveys required to establish large sample and to find the rare unique systems
Wavelength Coverage – >2 NIR filters for photo-z of both lenses and sources

Xiaohui Fan (University of Arizona), fan@as.arizona.edu

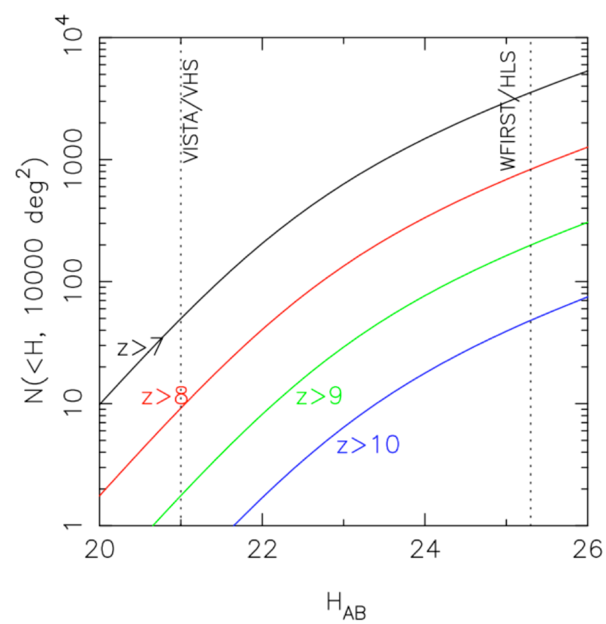
High-Redshift Quasars and Reionization

Background

Luminous quasars at high redshift provide direct probes of the evolution of supermassive black holes (BHs) and the intergalactic medium (IGM) at early cosmic time. The detection of z>7 quasars (e.g., Mortlock et al. 2011) indicates the existence of billion solar mass BHs merely a few hundred million years after the Big Bang, and provides the strongest constraints on the early growth of supermassive BHs and their environments. Spectroscopy of the highest redshift quasars reveals complete Gunn-Peterson (1965) absorption, indicating a rapid increase in the IGM neutral fraction and an end of the reionization epoch at z=6-7 (Fan et al. 2006). Current observations suggest a peak of reionization activity and emergence of the earliest galaxies and AGNs at 7<z<15, highlighting the need to expand quasar research to higher redshift.

WFIRST

While ground-based surveys such as LSST and VISTA will make progress in the z=7-8 regime in the coming decade, strong near-IR background from the ground will limit observations to the most luminous objects and to z<8. Wide-field, deep near-IR survey data offered by WFIRST will fundamentally change the landscape of early Universe investigations. Figure 1 shows the predicted number of high-redshift quasars in a WFIRST survey based on current measurements at z~6 (Jiang et al. 2008; Willott et al. 2010) and extrapolation to higher redshift with a declining number density following the trend seen at z=3-6. WFIRST should allow robust identifications of a large sample of reionization-epoch quasars up to z>10, if they exist at those epochs. WFIRST grism will provide direct spectroscopic confirmation and characterization of these high-redshift quasars, while JWST and next-generation extremely large telescope high-resolution spectroscopic observations will measure IGM and BH properties. Key questions to be addressed by these observations are: (1) when did the first generation of supermassive BHs emerge in the Universe; (2) how and when did the IGM become mostly neutral; (3) did quasars and AGNs play a significant role in the reionization process?



Key Requirements

Depth – To study sub-L* QSO populations at high redshift

Morphology – To separate stars from galaxies; one of the main contaminations is expected to be low-redshift red galaxies

Grism – For spectroscopic confirmation and characterization

Field of View – Wide-area surveys required to identify rare populations

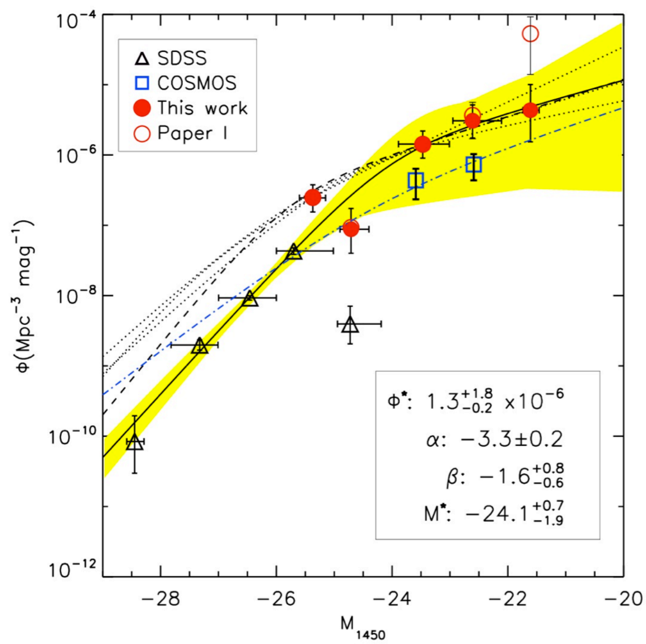
Wavelength Coverage – >2 NIR filters to robustly identify QSOs at the highest redshifts

Daniel Stern (JPL), daniel.k.stern@jpl.nasa.gov

The Faint End of the Quasar Luminosity Function

Background

The primary observable that traces the evolution of quasar (QSO) populations is the QSO luminosity function (QLF) as a function of redshift. The QLF can be well represented by a broken power-law: $\Phi(L) = \phi_*/[(L/L_*)\alpha + (L/L_*)\beta]$, where L_* is the break luminosity. Current measurements poorly constrain the corresponding break absolute magnitude to be $M_* \simeq -25$ to -26 at λ=1450 Å. The bright-end slope, α, appears to evolve and flatten toward high redshift, beyond z ~ 2.5 (Richards et al. 2006). The faint-end slope, β, is typically measured to be around −1.7 at z~2.1; it is poorly constrained at higher redshift, but appears to flatten at z ~ 3 (Siana et al. 2008). At yet higher redshift, however, the situation is much less clear due to the relatively shallow flux limits of most surveys to date. The true shape of the QLF at z > 4 is still not well measured, and the evolution of L_* and the faint-end slope remain poorly constrained (Glikman et al. 2010, 2011; Ikeda et al. 2010). Studying the faint end of the high-redshift QLF is important for understanding the sources responsible for re-ionizing the Universe. While Vanzella et al. (2010), studying faint z~4 galaxies in the GOODS fields, finds that Lyman-break galaxies (LBGs) account for <20% of the photons necessary to ionize the intergalactic medium (IGM) at that redshift, Glikman et al. (2011) find that QSOs can account for 60±40% of the ionizing photons. Furthermore, new quasar populations appear when one studies faint, high-redshift quasars. Glikman et al. (2007), in their initial work on the faint end of the high-redshift QLF, found strong NIV] 1486 emission in ~10% of the QSOs surveyed, likely associated with early starbursts.



Caption: QLF at z~4 from Glikman et al. (2011). Note the substantial uncertainties below the knee in the QLF.

WFIRST

The deep, wide-field imaging data from WFIRST DE surveys will provide critical information for constraining the faint end of the high-redshift QLF. While at z~4, deep ground-based data from surveys such as LSST will be essential, WFIRST grism spectroscopy will play an essential role in confirming the high-redshift AGN nature of the photometric candidates. At yet higher redshifts, z>7, deep surveys from WFIRST alone will probe the earliest epochs of nuclear activity.

Key Requirements

Depth – To study sub-L* QSO populations at high redshift

Morphology – To separate stars from galaxies (though note that faint QSOs at high redshift are likely to show significant host galaxy light, and thus morphology should be used to characterize the populations, but not as a selection criterion)

Grism – For spectroscopic confirmation and characterization

Field of View – Wide-area surveys required to identify rare populations

Wavelength Coverage – >2 NIR filters to robustly identify QSOs at the highest redshifts

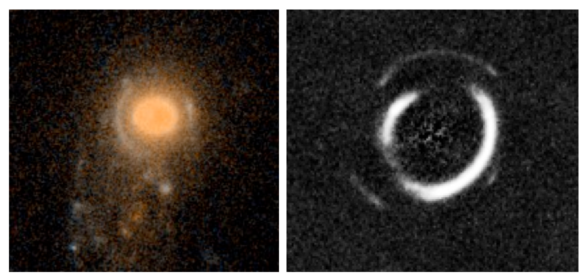
Daniel Stern (JPL), daniel.k.stern@jpl.nasa.gov

Strong Lensing

Background

Strong gravitational lensing is a remarkable physical phenomenon. Massive objects distort space-time to the extent that light sources lying directly along the line of sight behind them can appear multiply-imaged (see Schneider 2006 for a review). When this rare alignment occurs, we are given: (1) the opportunity to accurately infer the mass and mass distribution of the lensing object; and (2) a magnified view of the lensed source, often probing luminosities and size scales that would not be accessible with current technology. While the approximately 200 galaxy-scale strong lenses we know of currently generally come from low- resolution, ground-based surveys, the bulk of the scientific potential of these rare systems requires (and has relied upon) high-resolution follow-up studies with the Hubble Space Telescope (Fig. 1; e.g., Browne et al. 2003, Bolton et al. 2006). The same has been true for the similar number of cluster-scale strong lens systems (e.g., Smith et al. 2005).

Simply making a precise measurement of lens statistics provides cosmographic information from the total lens counts, the so-called "lens redshift test" (e.g., Capelo & Natarajan 2007). If the lens mass distribution is well-constrained, as in the case of "compound lenses", where multiple sources line up behind the lensing galaxy or cluster, the lens geometry can be used to measure ratios of distances — compound lenses are standard rods for probing the Universe's expansion kinematics with high precision (Golse et al. 2002, Gavazzi et al. 2008). However galaxy-scale compound lenses are rare, typically just 1% of galaxy-scale lenses, and only by imaging a substantial fraction of the sky can we find such golden lenses.



Caption: Strong gravitational lenses imaged with Hubble. WFIRST will increase the number of strong lenses known by a factor of ~100, thus also identifying rare configurations — such as lensed SNe, lenses with higher order catastrophes in their caustics, and compound (e.g., double lens-plane) lenses — which have even richer scientific potential. [From Moustakas et al. 2007 and Gavazzi et al. 2008.]

WFIRST

Based on Hubble surveys of a few square degrees, we expect strong lenses to have an abundance of about 10 per square degree (Faure et al. 2008), suggesting that the Hubble-era sample of lenses observed at high resolution will be expanded by several orders of magnitude by the WFIRST weak-lensing survey (e.g., Marshall et al. 2005), the majority of these will be galaxy-scale lenses. The number of observable galaxy-scale lenses is a very strong function of angular resolution: the factor of six degradation in resolution from a diffraction limited 1.5-meter space-based telescope relative to typical ground-based conditions incurs a two order of magnitude decrease in the number of lenses identifiable from the ground. WFIRST, with its high-resolution and wide-field capabilities, will revolutionize the field of strong gravitational lensing, enabling fundamental, new cosmological and astrophysical probes.

Key Requirements

Depth – To provide high S/N detections
Morphology – To precisely measure positions
Field of View – Wide-area to detect rare events
Wavelength Coverage – Single band sufficient

Sangeeta Malhotra and James Rhoads (ASU), Daniel Stern (JPL), daniel.k.stern@jpl.nasa.gov

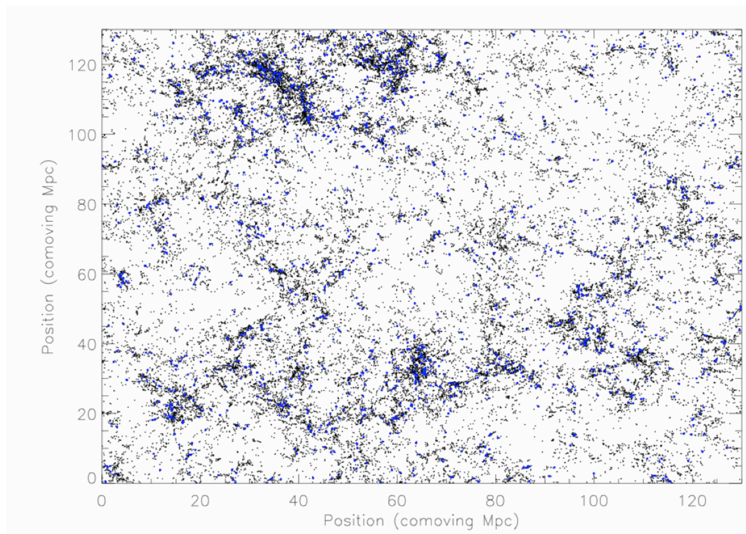
Probing the Epoch of Reionization with Lyman-Alpha Emitters

Background

Observations of the Gunn-Peterson effect in the most distant quasars tell us that the reionization of the Universe concluded at redshift z~6 (e.g., Fan et al. 2006). Since that time, the gas between the galaxies has remained largely ionized, while at earlier cosmic epochs this intergalactic medium (IGM) was largely neutral. The exact time, or times, that this cosmic phase change occurred is a fundamental question for galaxy formation, telling us both when the first generation of stars formed in the Universe and how much effect they had on their neighboring systems. Various observations paint potentially conflicting pictures of this “epoch of reionization”, with quasars suggesting a late reionization, and both the cosmic microwave background and Lyman-alpha emitting galaxies (LAEs) suggesting an earlier reionization. Theory suggests that multiple epochs of reionization are possible. WFIRST will be a premiere facility for studying the late stages of the cosmic reionization epoch (see Figure).

WFIRST

At the resolution of the WFIRST grism, LAEs will be easily identified from their strong, narrow Lyα emission and their diminished flux blue-ward of this emission. Simple arguments dictate that LAEs provide a powerful probe of reionization: Lyα photons injected into a neutral medium are strongly scattered, thus strongly suppressing, or even eliminating, detectable Lyα emission. The transmitted fraction depends upon the size of the local cosmological HII region surrounding the source, and therefore on the ionizing luminosity and age of the source (e.g., Santos 2004) as well as contributions from associated, clustered sources (e.g., Wyithe & Loeb 2004). Nevertheless, we expect a rapid decline in the observed space density of LAEs as the reionization epoch is approached: a statistical sample of LAEs spanning the reionization epoch, as the WFIRST grism would uniquely provide, will present an extremely robust probe and two-dimensional map of reionization (e.g., Malhotra & Rhoads 2004; Stern et al. 2005; Ouchi et al. 2010). In particular, such work will require much larger fields than are accessible with Hubble or expected to be observed with JWST.



Caption: Simulated large scale structure at z=6.6. Black dots are collapsed haloes, blue dots are LAEs. The blue box in the upper right corner shows the field of view of Hubble/ACS, illustrating that Hubble (and JWST) has much too small of a field of view to study the spatial distribution of LAEs. [Based on Tilvi et al. 2009]

Key Requirements

Depth – To provide high S/N detections

Morphology – To precisely measure positions

Field of View – Wide-area to detect rare events

Wavelength Coverage – Single band sufficient

Paul Schechter (MIT), schech@mit.edu

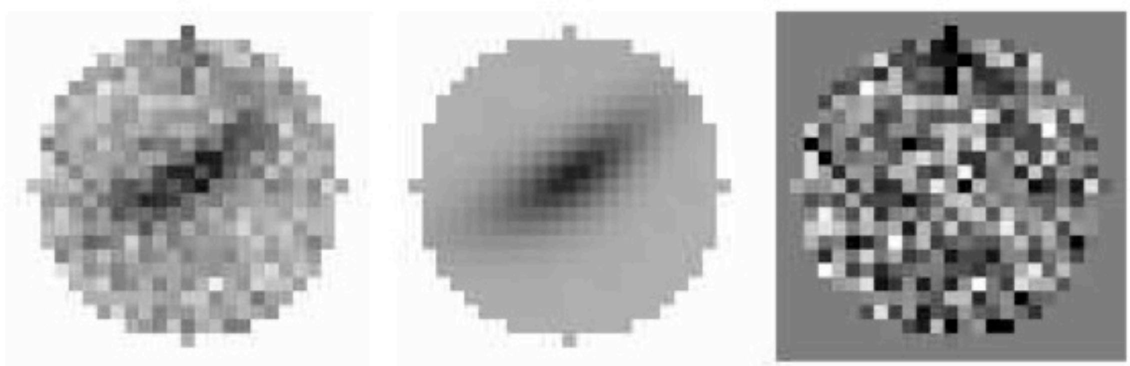
The Shapes of Galaxy Haloes from Gravitational Flexion

Background

Gravitational "flexion" is the next higher order gravitational lensing effect after shear (e.g. Bacon et al. 2006, MNRAS, 365, 414). Shear is proportional to second derivatives of the gravitational potential; flexion is proportional to third derivatives. Flexion causes otherwise symmetric galaxies to appear lopsided and curved. Flexions are greatest at relatively small distances from gravitational lenses – within roughly 10 Einstein radii. But while shear signals are degenerate with the much larger intrinsic ellipticities of lensed galaxies, the intrinsic lopsidedness and curvature of galaxies is quite small. A single flexion measurement can therefore give significant signal-to-noise. These properties make flexion a far better tool than shear for the study of the shapes of the dark matter haloes of galaxies (Hawken & Bridle 2009, MNRAS, 400, 1132; Er & Schneider 2011, A&A, 528, 52). But, this comes at the cost of deeper exposures. In order to take full advantage of the small intrinsic scatter in galaxy lopsidedness and curvature, one must obtain higher signal-to-noise.

WFIRST

The wider-versus-deeper question for shear measurements is quite subtle (e.g. Bernstein 2002, PASP, 114, 98), and it is even trickier for flexion measurements, but we suspect that the optimum depth will be somewhat closer to that achieved by WFIRST's supernova program than by its weak lensing program. Given the extraordinary ultimate power of flexion measurements – with uncertainties in the mean ellipticity of galaxy dark matter haloes of 0.00003 per steradian, according to Hawken & Bridle (2009) – flexion measurements in the supernova survey fields will, for the purpose of measuring galaxy halo shapes, be competitive with shear measurements over the much larger weak lensing survey.



Caption – A 30 minute Magellan exposure of a flexed galaxy observed in the Sloan r' filter (left), an intrinsically elliptical galaxy model distorted by flexion (center), and the difference between the two (right).